"OPTIMAL SIMULATION TECHNIQUES FOR DISTRIBUTED ENERGY STORE RAILGUNS WITH SOLID STATE SWITCHES"

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ABSTRACT

The objective of this paper is to present an optimal design methodology to determine the best firing strategy, energy store sizing, energy store spacing and maximum system efficiency for a Distributed Energy Store (DES) railgun. System simulations/designs will be based on the assumption that switching of the energy storage units will be accomplished using solid state devices. Candidate semiconductor technologies are promising in relation to solving the high energy, low weight requirements of a railgun system and other pulsed power systems requiring high energy, compact switching.

A simulation code has been developed and used to produce non-dimensional data files that are then scaled to physical railgun values based on input parameters. Energy stores are assumed to be capacitive in nature with diodes to prevent negative currents and crowbar diodes to prevent voltage reversal of the capacitors.

The main thrust of this simulation effort is to produce a DES design that optimizes the efficiency of the conversion of stored electrical energy to projectile kinetic energy, while also considering the abilities of near term solid state switching devices.

INTRODUCTION

Impetus for this work is derived from the Focused Technology Program (FTP) goals for launching of a projectile with a railgun[1]. Under the FTP program, a projectile is to be launched under the following parameter conditions:

Projectile Mass:	4.44 kg
Exit Velocity:	3.0 km/s
Barrel Length:	7.0 m

The FTP goals also state a barrel lifetime of 1000 shots and a multi-shot mission profile is given. For this work we will only consider the single shot mission.

Many other parameters are required to simulate or design a system that will meet the FTP goals. The selection of those parameters, the type of power supply, the methodology for simulating the system, and the results of the simulation and conversion program that outputs physical railgun parameters are discussed.

DES SYSTEM

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A DES system for a railgun is one that incorporates the use of many power supplies along the barrel instead of a single power supply placed at the breech, as in most conventional systems. One benefit of the DES configuration is that the barrel current is not flowing from the breech to the projectile at all times, as in a breech fed railgun.

An introduction to the circuit equations that are pertinent to railgun operation are presented by J. P. Barber[2] and J. B. Cornette[3], and the equations describing DES operation are presented well by J. V. Parker and R. A. Marshall[4,5].

Power Supplies

Power supplies for this work are assumed to be capacitor banks. Capacitors have proven high current capability, availability, and operating voltages that match well to railgun systems. However, the simulation can be modified to model other types of energy storage devices.

The capacitor banks are assumed to have crowbar diodes to prevent negative voltages from being impressed onto the capacitors and a diode in the forward current leg (see Figure 1) of each power supply to prevent negative currents from flowing into the capacitors. This forward leg diode precludes individual banks from discharging into the other capacitor banks. A single capacitor bank connected to the breech of a railgun is depicted in Figure 1.

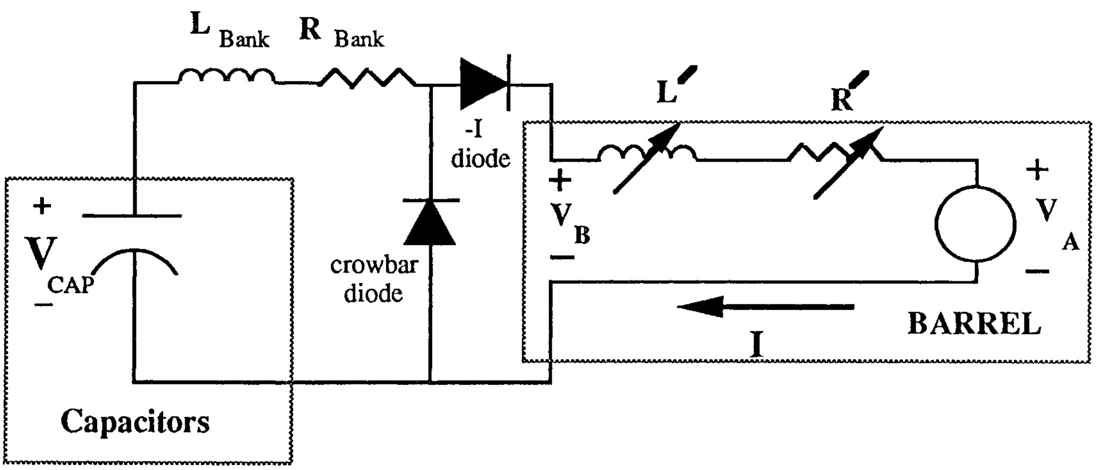

Figure 1. **Single Capacitor Bank, Breech Connected to an Railgun.**

The breech voltage of the barrel is represented by V_B, and the armature voltage of the projectile is V_A. The breech voltage is governed by the following equation and the armature voltage is assumed constant for this work. The type of armature that each user wishes to simulate will cause the value of V_A to vary tremendously and is up to the user to determine. The ability to interactively alter V_A prior to each run is an important capability of this simulation.

$$V_B = IR'x + V_A + \left[x\frac{\partial L}{\partial x}\frac{\partial I}{\partial t} + I\frac{\partial L}{\partial x}\frac{\partial x}{\partial t} \right]$$

Assuming L'=∂L/∂x, and L' & R' are independent of projectile position:

$$V_B = IR'x + V_A + L'x\frac{\partial I}{\partial t} + IL'v$$

In the DES case, each bank will see a different V_B depending on their connection point along the length of the barrel.

For this simulation each capacitor stage has a series inductance and resistance that can be set at the beginning of each run and banks are spaced evenly down the length of the barrel as discussed in the next section.

Barrel

In this case, the FTP goals set the barrel length to 7.0 m. From the equations of motion and Maxwell's equations, the force exerted on the projectile due to the interaction of the current density vector and the magnetic flux density vector result in the commonly known Lorentz force.

After determining the magnetic energy in terms if current (I) and position (x) and differentiating with respect to x we have the electric force on the projectile:

$$F_e = \frac{1}{2}\left[I^2\frac{\partial L}{\partial x} + 2IL\frac{\partial I}{\partial x}\right]$$

and assuming constant I for small ∂x:

$$F_e = \frac{1}{2}L'I^2$$

Which is in terms of the barrel inductance gradient ($L'=\partial L/\partial x$ in µH/m) and the current (I). This force is the basis for determining the optimum arrangement of power supplies along the barrel and constant force on the projectile, L' and I must be constant. The L' is assumed constant for this study and equal to 0.5 µH/m. The power supplies are assumed to store equal energy and are placed at equal distances down the barrel. In order to transfer the energy stored in each capacitor bank most efficiently to the projectile as the projectile's velocity increases, the open circuit voltage and capacitance of the banks are allowed to vary. By changing the time constant of the banks as the projectile moves down the barrel, the energy stages toward the muzzle discharge faster than those closer to the breech.

Allowing the capacitance and charge voltage of the energy stages to change is the most efficient method for the use of capacitor banks in a DES system (see figure 2), however, it is not as practical to build in reality. Therefore, the code has been altered to allow the user to choose whether or not they would like equal capacitance and voltage per stage as in a more realistic system. One design procedure would be to determine the optimum system using varying voltage and capacitance, then run the same system with equal voltage and capacitance. After several iterations, one can arrive at an approximation of the optimum system with a practical capacitor bank.

The loss parameters of armature voltage and rail resistance are interactively set by the user at the beginning of each run. The armature voltage is constant and the rail resistance is the gradient in Ω/m for one rail.

SIMULATIONS

The DES circuit solver used here is based on the work of J. V. Parker[5]. The circuit equations are solved in dimensionless form. Once an optimized solution is determined, as related to the users input parameters, a physical railgun design must be translated from the dimensionless data. The original code has been modified as stated above to allow equal voltage and capacitance per stage, increasing the energy storage of any of the stages, and increasing the number of energy stages to 100.

A second code has been written that takes the non-dimensional data from the FORTRAN circuit solving simulation and then produces a physical railgun data set, given certain input parameters. This conversion routine is a MATLAB based code that is capable of up to 100 individual energy stages.

Output from the MATLAB code shows the user how efficiently the energy was transferred to the projectile and various other parameters. A summary of those parameters are presented below:

Number of stages (N)	Maximum gun current
Circuit input parameters	Maximum gun di/dt
Energy stored	Maximum projectile acceleration
Energy transferred to projectile	Maximum bore pressure
System energy losses	Maximum back voltage (L'Iv)
Energy losses per stage	Maximum stage currents (1 to N)
Initial stage volts (1 to N)	Maximum stage di/dt's (1 to N)
Stage R, L, C's, etc.	

Many other parameters can be displayed and plotted for the user.

EXAMPLE SIMULATION RUN

As an example of the input, output and data plotting capabilities of the DES simulation and conversion program, a single run utilizing the ability to alter the energy storage of any stage and using the more efficient variable capacitance and voltage for each stage is summarized with the following results.

Example input parameters, required before running the simulation, for the FTP goals are given below:

Number of Stages	= 28	Bore size (square)	= 100 mm
Barrel Length	= 7.0 m	Mass of projectile	= 4.44 kg
Injection Velocity	= 0.098 km/s	Exit Velocity	= 3.0 km/s
L'	= 0.5 μH/m	Armature Voltage	= 9.577 V
R'	= 122.61 μΩ/m	Stage #1 Energy	= 2.97 * E_{i},i=1,28

An output summary for the FTP run is given below:

Total Stored Energy	= 28.576 MJ	Max. Stage Current	= 3.998 MA
Exit Energy	= 19.98 MJ	Max. Stage di/dt	= 37.981 kA/μs
Exit Time	= 4.759 ms	Max. back Voltage	= 5.413 kV
Gun losses	= 0.291 MJ	Stage #1 C	= 246.98 mF
Stage Losses	= 2.116 MJ	Stage#1 L	= 0.330 μH
Energy Efficiency	= 69.92 %	Stage#1 R	= 49.95 μΩ
Max. Bore Pressure	= 57.95 kpsi	Other Stage C's	= 2.9 to 41 mF
Max. Acceleration	= 91.80 kgee	Other Stage L's	= 0.980 μH
Max. Gun Current	= 3.998 MA	Other Stage R's	= 148.35μΩ
Exit Current	= 3.441 MA		

When increasing the energy storage of any bank, it is assumed that equal energy storage banks are connected in parallel (i.e., Increase the energy storage of stage#1 by 3.0, C1 =3*C_{old}, L1=L_{old}/3, R1=R_{old}/3).

A plot of the total gun current and the individual stage currents versus real time is presented in Figure 2. Notice that the first energy stage current is much higher than the others. This simulation run is an example of increasing the energy storage of the first stage in order to reach maximum gun current faster. In this example the energy storage of the first stage is approximately three times that of the other stages.

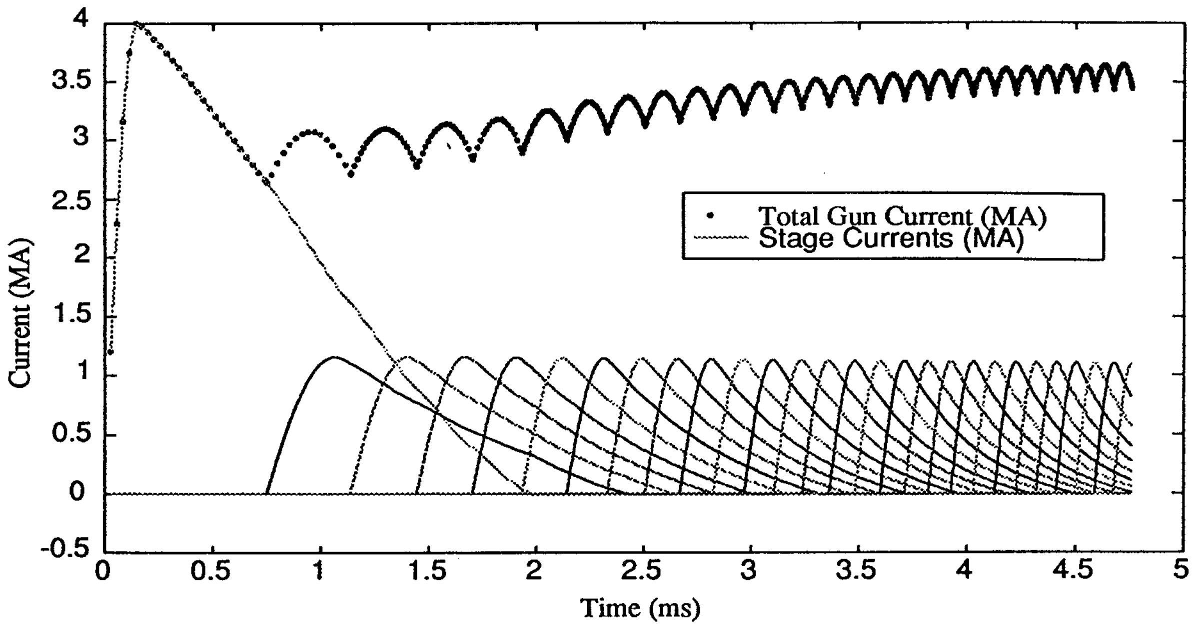

Figure 2. **Total Gun Current and Stage Currents versus Time**

Projectile acceleration in kgee is shown if Figure 3. If considering solid state devices for the closing switches for such a DES system, the individual stage maximum di/dt's are an important factor (among many others) that will determine if they can successfully perform the switching. Therefore, an example of individual stage di/dt's in kA/μs are shown in Figure 4. The maximum di/dt capability of potential solid state devices today is approximately 20 kA/μs.

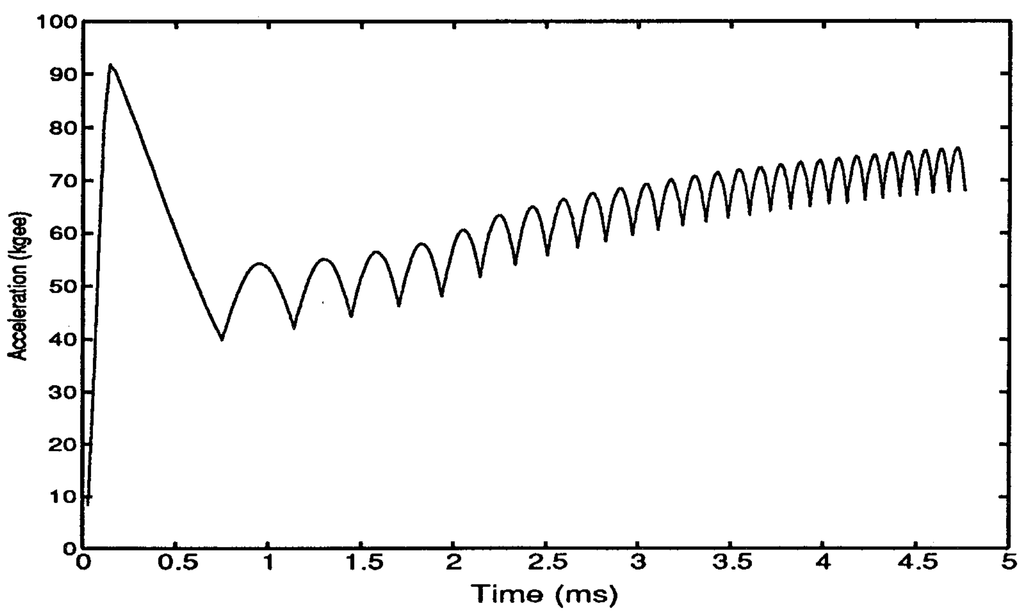

Figure 3. **Projectile Acceleration**

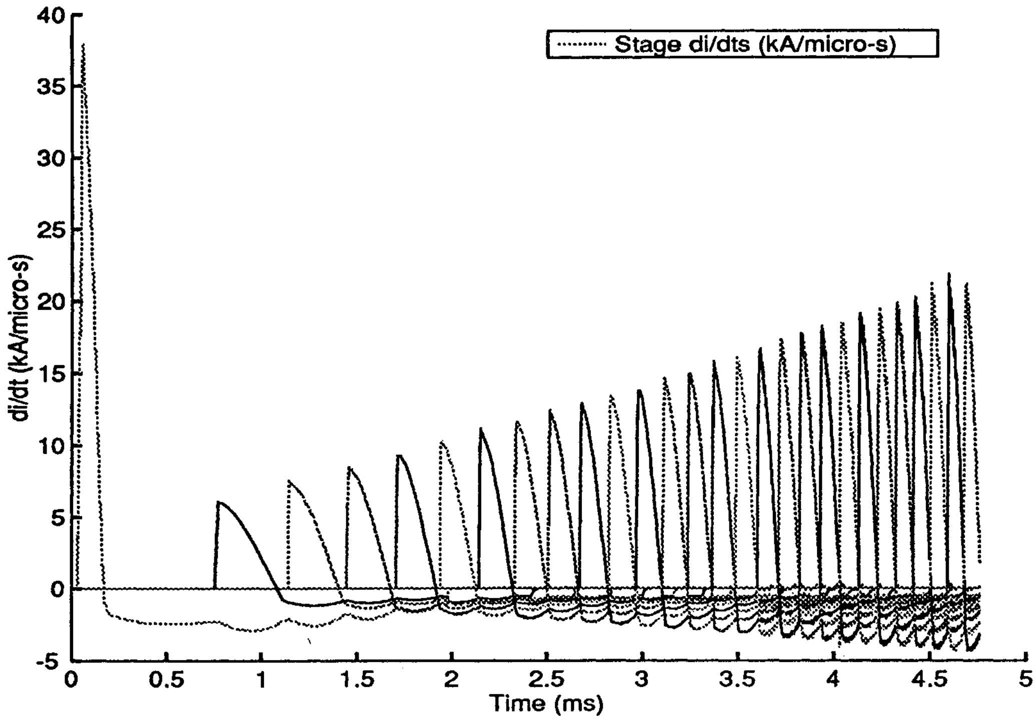

Figure 4. **Stage di/dt's**

SUMMARY

A practical DES railgun simulation code has been developed and used to complete first order system design for the FTP requirements. The methodology assumes equal energy storage in each stage, equal distance between stages, equal resistance and inductance per stage, and varying capacitance and charge voltage in each stage. Provisions have been made for the user to compare a system based on the above stated assumptions to one that has equal capacitance and voltage in each stage. The energy storage of any stage can also be adjusted to reach the maximum driving current faster than would normally occur in a DES system of equal energy stages.

Future work will be directed towards adding solid state device characteristics to the code to enable design of switching schemes for each stage. Once complete, the long term goal is to construct an easy to use interactive interface application for users to design a complete DES system according to the type of energy storage units, switching devices, and barrel parameters desired.

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